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Goeke

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(54) **ACTIVE SHUNT AMMETER APPARATUS AND METHOD**

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(*) Notice: Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 116 days.

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(51) **Int. Cl.**

G01R 1/30 (2006.01)
G01R 1/20 (2006.01)
H03F 3/45 (2006.01)
G01R 19/00 (2006.01)
H03F 1/34 (2006.01)

(52) **U.S. Cl.**

CPC ***G01R 1/203*** (2013.01); ***H03F 3/45475*** (2013.01); *G01R 19/0023* (2013.01); *G01R 19/0092* (2013.01); *H03F 1/34* (2013.01); *H03F 2200/261* (2013.01); *H03F 2203/45138* (2013.01)

(58) **Field of Classification Search**

CPC G01R 15/185; G01R 15/205; G01R 19/20
USPC .... 324/123 R, 123, 76, 117, 121, 122
See application file for complete search history.

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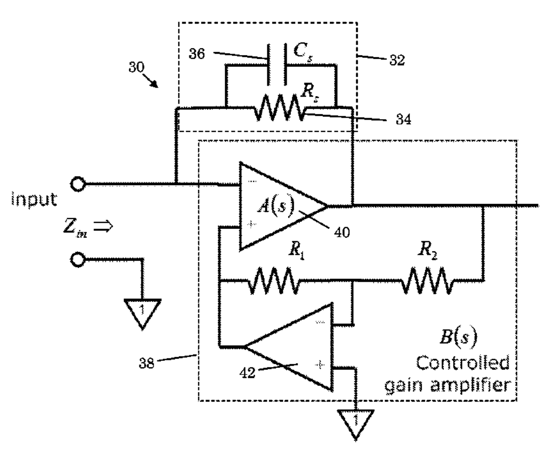
(57) **ABSTRACT**

An active shunt ammeter for measuring current flowing through a device under test (DUT) and method are disclosed. The active shunt ammeter includes an input configured to receive an input signal having a frequency within a frequency band and representing the current flowing through the DUT. An output is configured to generate an output voltage representing the current flowing through the DUT. The active shunt ammeter also includes a gain circuit having an amplifier with a gain characteristic that varies respect to frequency within the frequency band and a feedback element having an impedance coupled from an output of the gain circuit to a negative input of the gain circuit, the feedback element impedance being configured to change with frequency to correlate with the amplifier gain characteristic such that the feedback element impedance divided by the amplifier gain over the frequency band has minimal frequency dependency.

16 Claims, 7 Drawing Sheets



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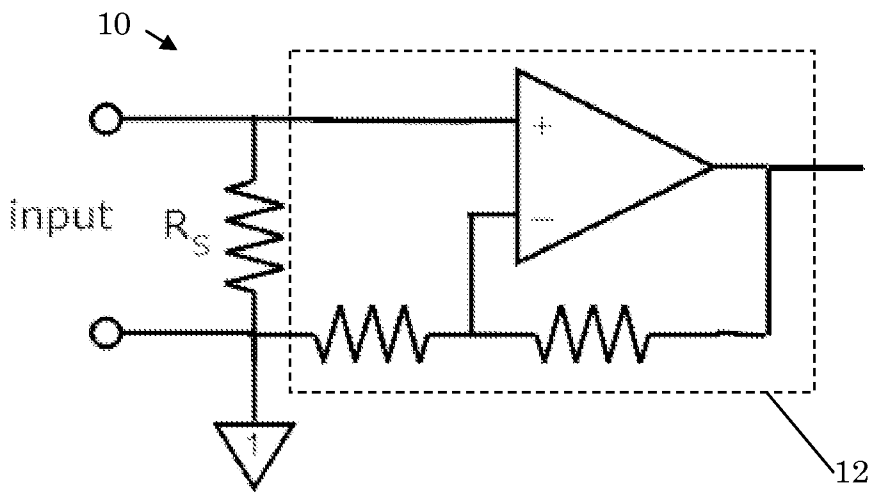


Figure 1A
(Prior Art)

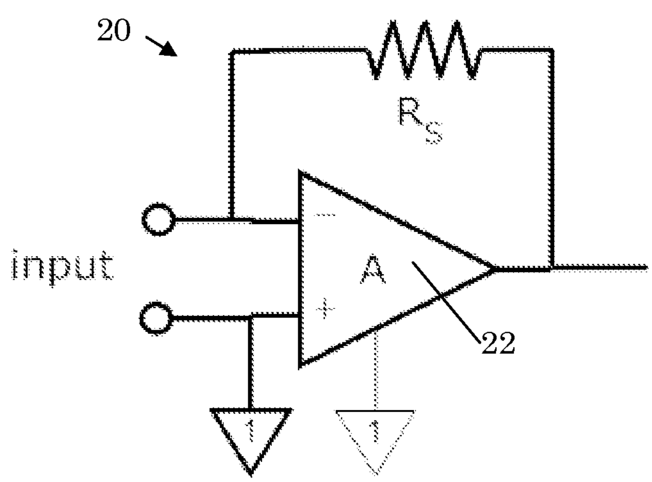
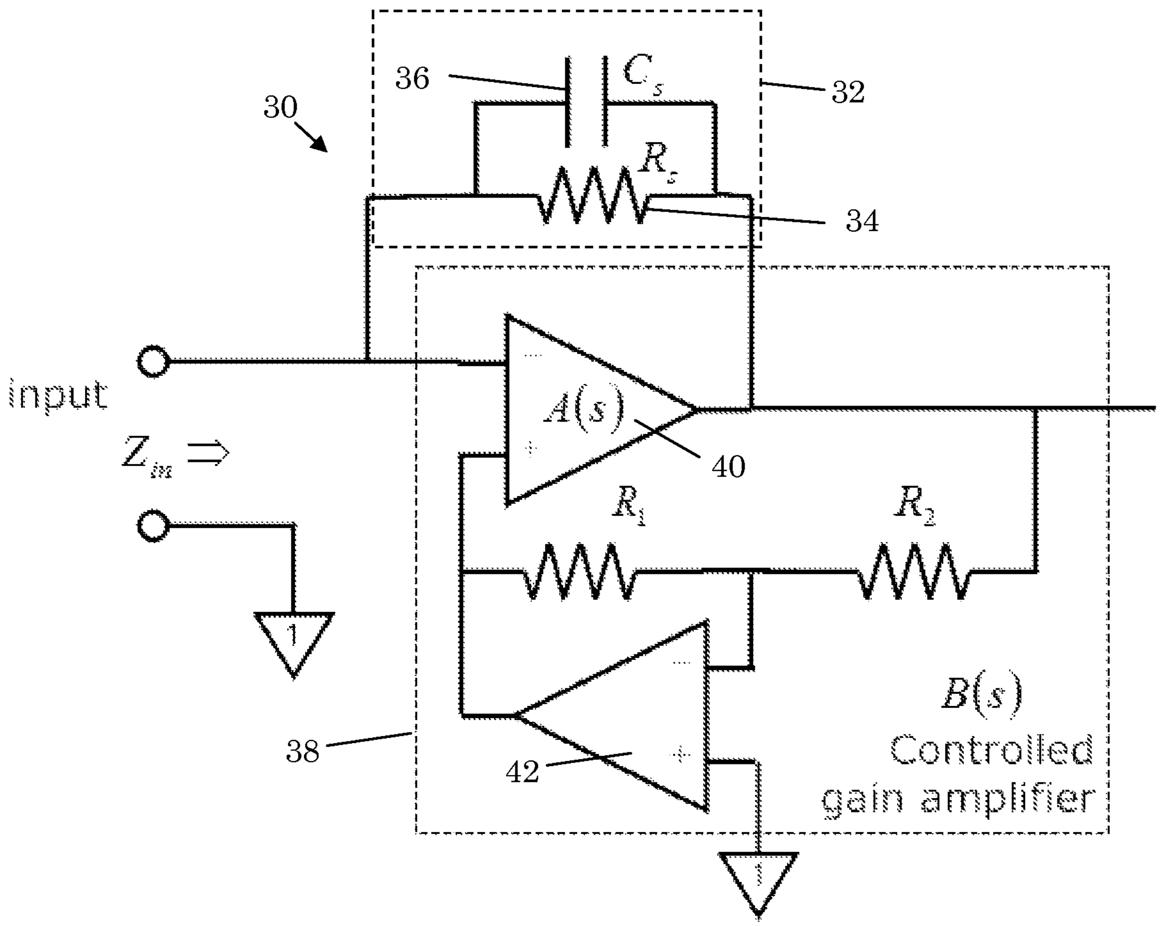
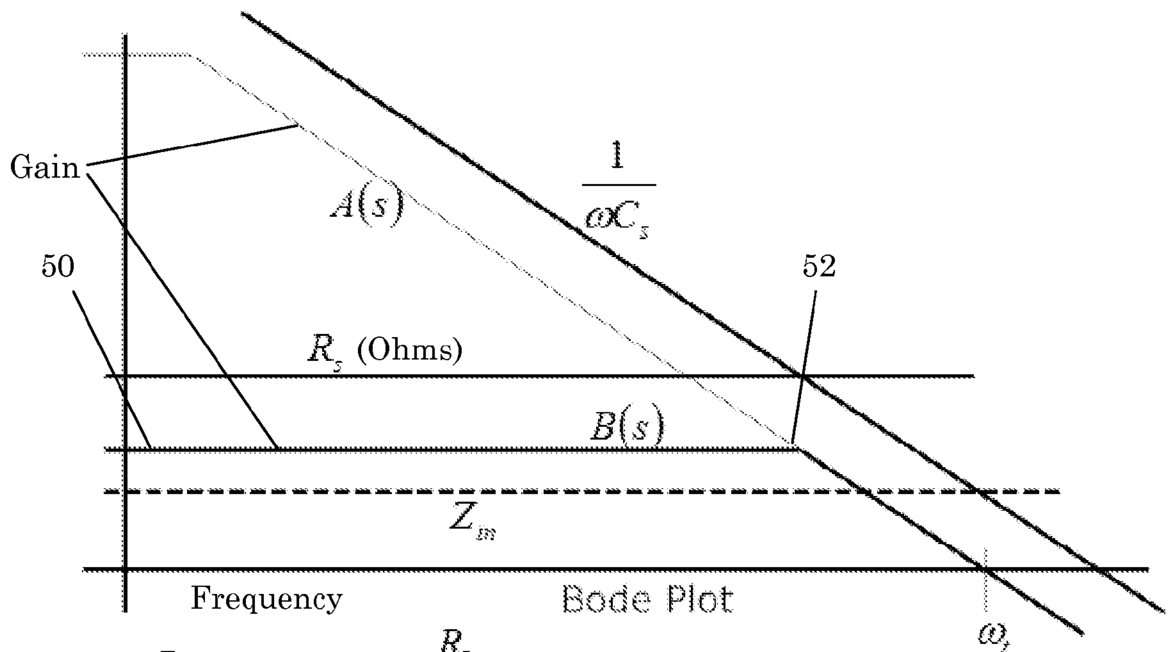


Figure 1B
(PriorArt)



36
C_s
32
30
R_s
34
input
$Z_{in} \Rightarrow$
$A(s)$
40
R_1
R_2
$B(s)$
Controlled
gain amplifier
38
42

Figure 2A



$Z_{in} = R_s \frac{R_1}{R_2}$ $C_s \approx \frac{R_2}{\omega_t R_s R_1}$ $R_2 >> R_1$

Figure 2B

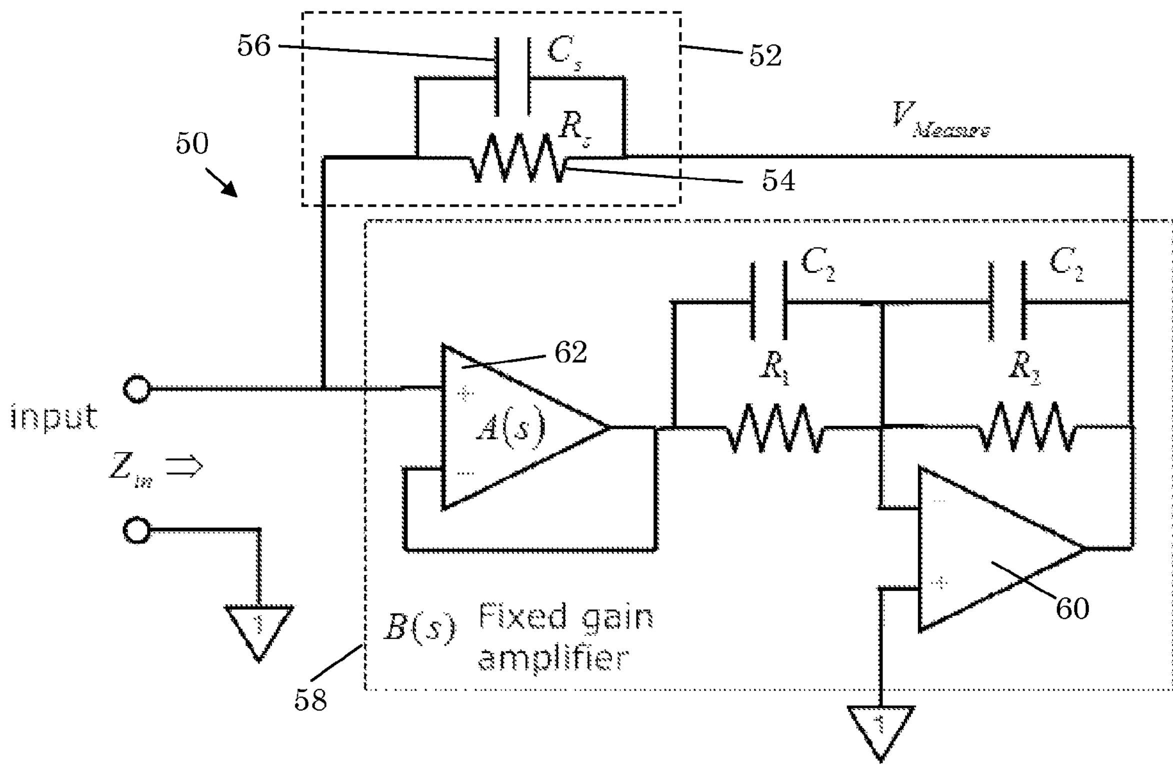
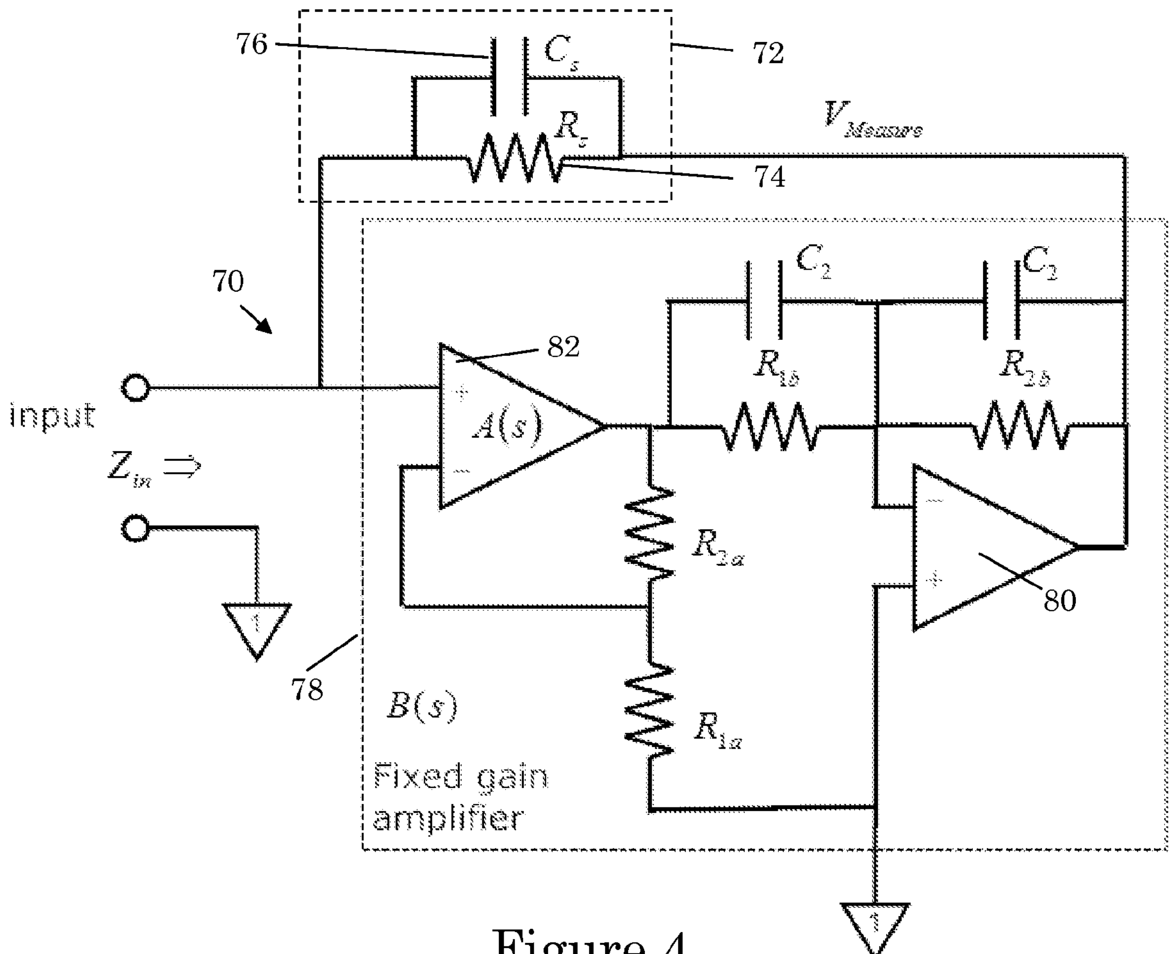

56
C_s
52
$V_{Measure}$
50
R_s
54
C_2
C_2
62
R_1
R_2
input
$Z_{in} \Rightarrow$
$A(s)$
60
$B(s)$ Fixed gain amplifier
58

Figure 3



76
C_s
72
R_s
$V_{Measure}$
74
70
C_2
C_2
82
R_{1b}
R_{2b}
input
$A(s)$
$Z_{in} \Rightarrow$
R_{2a}
80
78
$B(s)$
R_{1a}
Fixed gain
amplifier

Figure 4

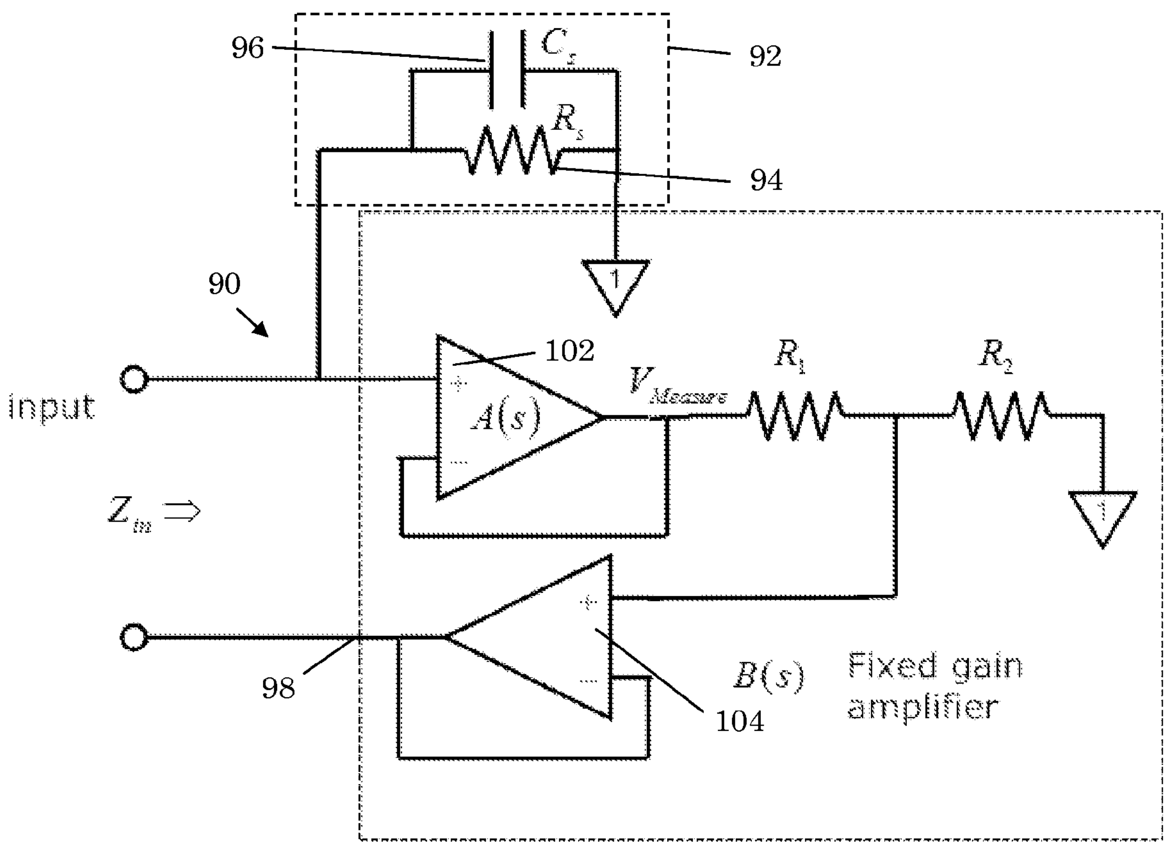

96
92
C_s
R_s
94
90
102
input
$V_{Measure}$
R_1
R_2
$A(s)$
$Z_{in} \Rightarrow$
98
$B(s)$
Fixed gain
amplifier
104

Figure 5

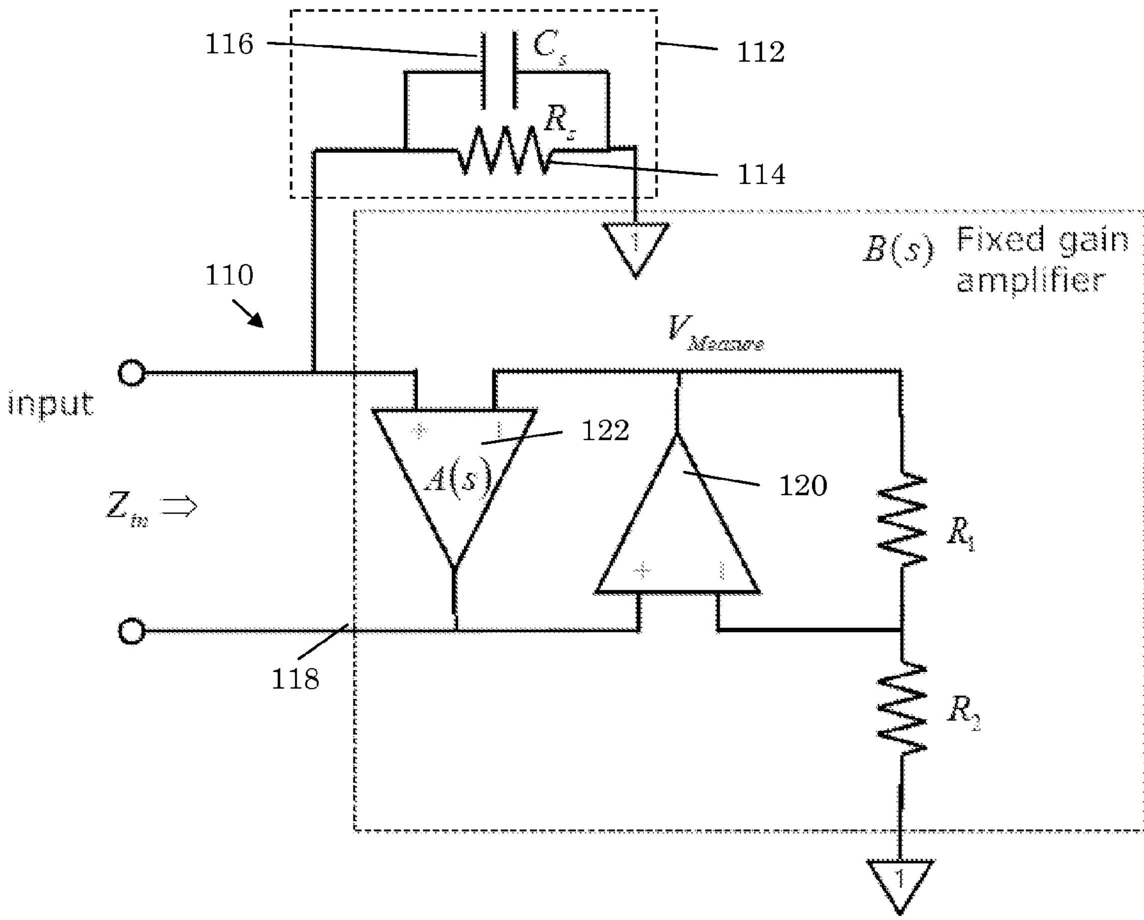

116
C_s
112
R_s
114
$B(s)$ Fixed gain amplifier
110
$V_{Measure}$
input
122
$A(s)$
120
$Z_{in} \Rightarrow$
R_1
118
R_2

Figure 6

ACTIVE SHUNT AMMETER APPARATUS AND METHOD

FIELD OF INVENTION

This invention relates generally to electrical measurement equipment and, in particular, to an active shunt ammeter for use in measuring electrical current.

BACKGROUND

Source measure units (SMU) are used to make precision measurements in many fields, including the testing of semiconductor products. For example, U.S. Pat. No. 5,039,934 describes one such device and range-changing in such a device is described in U.S. Pat. No. 5,144,154, both of which are incorporated herein by reference in their entireties. Typical SMU designs include a voltage or current source with integrated voltage and current measurement capabilities. A device under test (DUT) is coupled to the SMU and is then stimulated with either the voltage or current source.

There are several ways in which the current through a DUT may be measured. For example, a shunt ammeter, may be used to simply sense the voltage across a resistor R_S. R_S must be kept small to not cause a large burden voltage to the input signal. A low noise gain stage is required to amplify the burden voltage so it can be measured.

A feedback ammeter uses a high gain op-amp to pull the input circuit through the resistor R_S. The op-amp keeps the burden voltage low because of its high dc gain (typically greater than 1 million). This allows R_S to be larger allowing the output signal to be larger. However, the op-amps high gain begins to roll off at relatively low frequencies. This causes the burden voltage to increase at higher frequencies as well. If the input is capacitive, it can cause the feedback ammeter to ring or even oscillate. It would be desirable to provide improved ammeter configurations that address these problems.

SUMMARY OF THE INVENTION

An active shunt ammeter for measuring current flowing through a device under test (DUT) and method are disclosed. The active shunt ammeter includes an input configured to receive an input signal having a frequency within a frequency band and representing the current flowing through the DUT. An output is configured to generate an output voltage representing the current flowing through the DUT. The active shunt ammeter also includes a gain circuit having an amplifier with a gain characteristic that varies respect to frequency within the frequency band and a feedback element having an impedance coupled from an output of the gain circuit to a negative input of the gain circuit, the feedback element impedance being configured to change with frequency to correlate with the amplifier gain characteristic such that the feedback element impedance divided by the amplifier gain over the frequency band has minimal frequency dependency.

The amplifier may have a parallel RC feedback element. The amplifier may be a differential amplifier with a parallel RC feedback element coupled between a negative-input terminal and an output terminal. The gain circuit may have an input impedance that remains generally constant across the entire bandwidth of the amplifier based on the gain characteristic and the feedback element impedance. The amplifier may have a controlled negative gain across the feedback element. The amplifier may have an inverting stage having a gain set by a resistor ratio. The amplifier may have a gain that is split between two operational amplifiers (op-amps). A voltage across the feedback element may be buffered and attenuated by a resistor ratio. The amplifier may have an input op-amp with a gain placed in its feedback path.

A method of measuring current flowing through a device under test (DUT) is also disclosed, the method includes receiving an input signal having a frequency within a frequency band and representing the current flowing through the DUT. An output voltage is generated, the output voltage representing the current flowing through the DUT. A gain circuit is provided. The gain circuit has an amplifier with a gain characteristic that varies respect to frequency within the frequency band and a feedback element having an impedance coupled from an output of the gain circuit to a negative input of the gain circuit, the feedback element impedance being configured to change with frequency to correlate with the amplifier gain characteristic such that the feedback element impedance divided by the amplifier gain over the frequency band has minimal frequency dependency.

The amplifier may have a parallel RC feedback element. The amplifier may be a differential amplifier with a parallel RC feedback element coupled between a negative-input terminal and an output terminal. The gain circuit may have an input impedance that remains generally constant across the entire bandwidth of the amplifier based on the gain characteristic and the feedback element impedance. The amplifier may have a controlled negative gain across the feedback element. The amplifier may have an inverting stage having a gain set by a resistor ratio. The amplifier may have a gain that is split between two operational amplifiers (op-amps). A voltage across the feedback element may be buffered and attenuated by a resistor ratio. The amplifier may have an input op-amp with a gain placed in its feedback path.

BRIEF DESCRIPTION OF THE FIGURES

FIG. **1**A is a basic diagram of a shunt ammeter configured to simply sense the voltage across a resistor R_S;

FIG. **1**B is a basic diagram of a feedback ammeter configured with a high gain op-amp to pull the input circuit through a resistor R_S;

FIG. **2**A is an active shunt ammeter design using a controlled negative gain across a parallel RC feedback element;

FIG. **2**B is a graph showing the gain B(s) of the fixed gain amplifier of the active shunt ammeter in FIG. **2**A;

FIG. **3** is an active shunt ammeter design with a fixed gain amplifier constructed using an inverting stage where the inverting gain is set by a resistor ratio;

FIG. **4** is an active shunt ammeter design with a fixed gain amplifier where the gain is split between two op-amps;

FIG. **5** is an active shunt ammeter design with a fixed gain amplifier where the voltage across the shunt is buffered and slightly attenuated by a resistor ratio; and

FIG. **6** is an active shunt ammeter design with a fixed gain amplifier where the input op-amp has a slight gain placed in its feedback path.

DETAILED DESCRIPTION OF THE INVENTION

The disclosure herein relates generally to electrical measurement equipment and, in particular, to an active shunt ammeter for use in measuring electrical current. Such ammeters are often a sub component of measurement products including digital multi-meters (DMM) and source measure units (SMU). There are several ways in which the current through a device under test (DUT) may be measured. FIG. **1**A is a basic diagram of a shunt ammeter **10** configured to simply sense the voltage across the resistor R_S. R_S must be kept small to not cause a large burden voltage to the input signal. A low noise gain stage **12** amplifies the burden voltage so it can be measured.

FIG. **1**B is a basic diagram of a feedback ammeter **20** configured with a high gain op-amp to pull the input circuit through the resistor R_S. The operational amplifier (op-amp) **22** keeps the burden voltage low because of its high dc gain (typically greater than 1 million). This allows R_S to be larger allowing the output signal to be larger. However, the op-amps high gain begins to roll off at relatively low frequencies. This causes the burden voltage to increase at higher frequencies as well. If the input is capacitive, it can cause the feedback ammeter to ring or even oscillate.

An active shunt ammeter design addresses these problems. An active shunt ammeter configuration generally replaces the op-amp used in the feedback ammeter with a fixed gain amplifier. The result is a gain that is constant to higher frequencies. At the frequency the amplifier begins to roll off, the capacitor impedance ($1/j\omega C_s$) is designed to equal R_S. The roll off of the parallel impedance of R_S and C_s combined with the roll off the amplifier's gain, results in an input-impedance of the ammeter that is constant across the entire bandwidth of the amplifier. The result is a shunt like ammeter with higher output signal vs. burden voltage than a traditional shunt ammeter and none to the stability issues of feedback ammeters.

FIG. **2**A is an active shunt ammeter design **30** using a controlled negative gain across a parallel RC feedback element **32** such that input impedance of the circuit is a resistance equal to the R divided by the gain. In this example, the active shunt ammeter **30** includes a fixed gain differential amplifier **38** with a parallel resistor **34** and capacitor **36** connected between the negative-input and output terminals of the fixed gain differential amplifier **38**. The RC product of resistor **34** and capacitor **36** is selected to equal to the amplifier's gain-bandwidth divided by the fixed gain.

FIG. **2**B is a graph showing the gain B(s) of the fixed gain amplifier **38** as well as other parameters. In general, the gain B(s) (shown by reference number **50**) of fixed gain amplifier **38** remains essentially constant from DC until a target frequency **52**. Once the target frequency **52** is reached, the gain B(s) of the fixed gain amplifier **38** rolls off, e.g., at 20 db per decade. In this example, the operational amplifier **40** in FIG. **2**A has a gain A(s) that is much higher than B(s). However, operational amplifier **42** functions as an inverter in the feedback path yielding the composite gain B(s) for the fixed gain amplifier **38**. This configuration provides a controlled negative gain across the parallel RC feedback element **34**, **36** such that input impedance of the circuit is a resistance equal to the R_S divided by the gain.

In FIG. **2**A, ω_t is the gain bandwidth of the operational amplifier **40**. Also shown in FIG. **2**A is the resistance of resistor **34** (R_s) which remains constant over the frequency range shown. Also shown in FIG. **2**A is the input impedance Z_{in} of the active shunt ammeter **30**. In general, the input impedance Z_{in} configured to be significantly less than R_S and to appear to be resistive in nature to a frequency than is equal to or greater than ωt. In this example: $Z_{in}=R_s*(R_1/(R_1+R_2))$, $Cs\sim R_2/(\omega_t*R_s*R_1)$ and $R_2>>R_1$.

If the feedback element **32** was resistive only, i.e., capacitor **36** was omitted, the input impedance Z_{in} would increase with frequency after the target frequency **52**. The impedance of capacitor **36** may be selected to equal the impedance of the resistor at the target frequency **52**. This causes the impedance of the feedback element **32** to drop at the same frequency the operational amplifier **40** begins to roll off. This configuration yields a flat input impedance that does not roll off after the target frequency **52** as shown in FIG. **2**B.

It should be understood that a fixed gain amplifier may be implemented in several configurations. FIG. **3** is an active shunt ammeter design **50** with a fixed gain amplifier **58** constructed using an inverting stage where the inverting gain is set by R_2/R_1. Capacitance, C_2, is added across both resistors R_1, R_2 to reduce the inverting gain to one at the frequency the input buffer is starting to roll off approaching ω_t. In this example: $Z_{in}=R_s*(R_1/R_2)$ and $C_2\sim 1/(\omega_t*R_{1b})=R_s*C_s/R_{2b}$.

FIG. **4** is an active shunt ammeter design **70** with a fixed gain amplifier **78** where the gain is split between the op-amps **80**, **82**. In this example: $Z_{in}=R_s*(R_{1a}*R_{1b})/(R_{2a}*R_{2b})$ and $Cs\sim 1/(\omega_t*R_1)=(R_s*C_s)/R_2$.

FIG. **5** is an active shunt ammeter design **90** with a fixed gain amplifier **98** where the voltage across the shunt is buffered and slightly attenuated by a resistor ratio, R2/(R1+R2). In general, the attenuated signal is buffered and drives low side of the input. In this example: $Z_{in}=R_s*(R_1/(R_1+R_2))$.

FIG. **6** is an active shunt ammeter design **110** with a fixed gain amplifier **118** where the input op-amp **122** has a slight gain placed in its feedback. This causes the input op-amp to be a buffer with its output a little less than one, R2/(R1+R2). In this example: $Z_{in}=R_s*(R_1/(R_1+R_2))$.

It should be understood that many variations are possible based on the disclosure herein. Although features and elements are described above in particular combinations, each feature or element can be used alone without the other features and elements or in various combinations with or without other features and elements.

What is claimed is:

1. An active shunt ammeter for measuring current flowing through a device under test (DUT), the active shunt ammeter comprising:

an input configured to receive an input signal having a frequency within a frequency band and representing the current flowing through the DUT;

an output configured to generate an output voltage representing the current flowing through the DUT; and

a gain circuit having an amplifier with a gain characteristic that varies respect to frequency within the frequency band and a parallel RC feedback element having an impedance coupled from an output of the gain circuit to a negative input of the gain circuit, the feedback element impedance being configured to change with frequency to correlate with the amplifier gain characteristic, the amplifier being characterized by a roll-off frequency, and, at the roll-off frequency of the amplifier, an impedance of a resistive element in the parallel RC feedback element is substantially the same as an impedance of a capacitive element in the parallel RC feedback element.

2. The active shunt ammeter of claim **1**, wherein the amplifier is a differential amplifier with the parallel RC feedback element coupled between a negative-input terminal and an output terminal.

3. The active shunt ammeter of claim **1**, wherein the gain circuit has an input impedance that remains generally constant across the entire bandwidth of the amplifier based on the gain characteristic and the feedback element impedance.

4. The active shunt ammeter of claim **1**, wherein the amplifier has a controlled negative gain across the feedback element.

5. The active shunt ammeter of claim **1**, wherein the amplifier has an inverting stage having a gain set by a resistor ratio.

6. The active shunt ammeter of claim **1**, wherein the amplifier has a gain that is split between two operational amplifiers (op-amps).

7. The active shunt ammeter of claim 1, wherein a voltage across the feedback element is buffered and attenuated by a resistor ratio.

8. The active shunt ammeter of claim 1, wherein the amplifier has an input op-amp with a gain placed in its feedback path.

9. A method of measuring current flowing through a device under test (DUT), the method comprising:

receiving an input signal having a frequency within a frequency band and representing the current flowing through the DUT;

generating an output voltage representing the current flowing through the DUT; and

providing a gain circuit having an amplifier with a gain characteristic that varies respect to frequency within the frequency band and a parallel RC feedback element having an impedance coupled from an output of the gain circuit to a negative input of the gain circuit, the feedback element impedance being configured to change with frequency to correlate with the amplifier gain characteristic, the amplifier being characterized by a roll-off frequency, and, at the roll-off frequency of the amplifier, an impedance of a resistive element in the parallel RC feedback element is substantially the same as an impedance of a capacitive element in the parallel RC feedback element.

10. The method of claim 9, wherein the amplifier is a differential amplifier with a parallel RC feedback element coupled between a negative-input terminal and an output terminal.

11. The method of claim 9, wherein the gain circuit has an input impedance that remains generally constant across the entire bandwidth of the amplifier based on the gain characteristic and the feedback element impedance.

12. The method of claim 9, wherein the amplifier has a controlled negative gain across the parallel RC feedback element.

13. The method of claim 9, wherein the amplifier has an inverting stage having a gain set by a resistor ratio.

14. The method of claim 9, wherein the amplifier has a gain that is split between two operational amplifiers (op-amps).

15. The method of claim 9, wherein a voltage across the feedback element is buffered and attenuated by a resistor ratio.

16. The method of claim 9, wherein the amplifier has an input op-amp with a gain placed in its feedback path.

* * * * *

UNITED STATES PATENT AND TRADEMARK OFFICE

CERTIFICATE OF CORRECTION

PATENT NO. : 9,274,145 B2
APPLICATION NO. : 13/657549
DATED : March 1, 2016
INVENTOR(S) : Wayne C. Goeke

It is certified that error appears in the above-identified patent and that said Letters Patent is hereby corrected as shown below:

Title Page

Error reads:

(73) Assignee: TEKTRONIX, INC., Beaverton, OR (US)

Correction reads:

(73) Assignee: KEITHLEY INSTRUMENTS, INC., Cleveland, OH (US)

Signed and Sealed this
Sixth Day of December, 2016

Michelle K. Lee

Michelle K. Lee
Director of the United States Patent and Trademark Office